A new saccadic indicator of peripheral vestibular function based on the video head impulse test

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Abstract: Objective: While compensatory saccades indicate vestibular loss in the conventional head impulse test paradigm (HIMP), in which the participant fixates an earth-fixed target, we investigated a complementary suppression head impulse paradigm (SHIMP), in which the participant is fixating a head-fixed target to elicit anticompensatory saccades as a sign of vestibular function. Methods: HIMP and SHIMP eye movement responses were measured with the horizontal video head impulse test in patients with unilateral vestibular loss, patients with bilateral vestibular loss, and in healthy controls. Results: Vestibulo-ocular reflex gains showed close correlation (R2 = 0.97) with slightly lower SHIMP than HIMP gains (mean gain difference 0.06 ± 0.05 SD, $p < 0.001$). However, the 2 paradigms produced complementary catch-up saccade patterns: HIMP elicited compensatory saccades in patients but rarely in controls, whereas SHIMP elicited large anticompensatory saccades in controls, but smaller or no saccades in bilateral vestibular loss. Unilateral vestibular loss produced covert saccades in HIMP, but later and smaller saccades in SHIMP toward the affected side. Cumulative HIMP and SHIMP saccade amplitude differentiated patients from controls with high sensitivity and specificity. Conclusions: While compensatory saccades indicate vestibular loss in conventional HIMP, anticompensatory saccades in SHIMP using a head-fixed target indicate vestibular function. SHIMP saccades usually appear later than HIMP saccades, therefore being more salient to the naked eye and facilitating vestibulo-ocular reflex gain measurements. The new paradigm is intuitive and easy to explain to patients, and the SHIMP results complement those from the standard video head impulse test. Classification of evidence: This case-control study provides Class III evidence that SHIMP accurately identifies patients with unilateral or bilateral vestibulopathies.

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A new saccadic indicator of peripheral vestibular function based on the video head impulse test

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Contributions
GMH discovered the SHIMP saccade; HGM designed and built the vHIT system, programmed and analyzed the data, completed the statistical analysis, tested participants and patients and developed the model; KPW tested participants and patients, analyzed the data and wrote the paper; LAM tested participants and patients; SJR developed the iPad VOR model for generating the supplementary videos; LM tested participants and patients and assisted in writing; AMB assisted with analysis, figures and writing; ISC analyzed data, completed the statistical analysis and wrote the paper.

Disclosure
GMH, ISC, HGM, LAM, KPW act as unpaid consultants and have received funding for travel and free equipment for beta testing from GN Otometrics. However, the study was conducted with a custom-built, non-commercial prototype and the authors have no commercial interest in video head impulse systems. LM, SJR and AMB report no disclosures.

Abbreviations
VOR: vestibulo-ocular reflex
vHIT: video head impulse test
UVL: unilateral vestibular loss
BVL: bilateral vestibular loss
HIMP: conventional head impulse paradigm, where the participants must try to maintain gaze on an earth-fixed target during a brief, unpredictable head turn
SHIMP: suppression head impulse paradigm, where the participants must try to maintain gaze on a target from a head-mounted light projected onto the wall
ROC: Receiver operating characteristic
AUC: Area under the curve

ABSTRACT

Objective: While compensatory saccades indicate vestibular loss in the conventional head impulse test paradigm (HIMP), where the participant fixates an earth-fixed target, we investigated a complementary suppression head impulse paradigm (SHIMP), where the participant is fixating a head-fixed target to elicit anti-compensatory saccades as a sign of vestibular function.

Methods: HIMP and SHIMP eye movement responses were measured with the horizontal video head impulse test (vHIT) in patients with unilateral vestibular loss (UVL), bilateral vestibular loss (BVL) and healthy controls.

Results: Vestibulo-ocular reflex (VOR) gains showed close correlation (R^2=0.97) with slightly lower SHIMP than HIMP gains (mean gain difference 0.06±0.05 SD, $p<0.001$). However, the two paradigms produced complementary catch-up saccade patterns: HIMP elicited compensatory saccades in patients but rarely in controls, whereas SHIMP elicited large anti-compensatory saccades in controls, but smaller or no saccades in BVL. UVL produced covert saccades in HIMP, but later and smaller saccades in SHIMP towards the affected side. Cumulative HIMP and SHIMP saccade amplitude differentiated patients from controls with high sensitivity and specificity.

Conclusions: While compensatory saccades indicate vestibular loss in conventional HIMP, anti-compensatory saccades in SHIMP using a head-fixed target indicate vestibular function. SHIMP saccades usually appear later than HIMP saccades, therefore being more salient to the naked eye and facilitating VOR gain measurements. The new paradigm is intuitive and easy to explain to patients, and the SHIMP results complement those from standard vHIT.

Classification of Evidence: This case-control study provides Class III evidence that SHIMP accurately identifies patients with unilateral or bilateral vestibulopathies.

INTRODUCTION

In the conventional head impulse paradigm (HIMP) the compensatory saccade is an indicator of semicircular canal loss.[1-4] Here the patient is instructed to maintain fixation on an earth-fixed target during head rotation towards their tested ear (Video 1). In patients with vestibular loss the vestibulo-ocular reflex (VOR) does not correct for the head movement, so that fixation is taken off the target, requiring a compensatory saccade to regain the target (Videos 2, 3). In contrast, healthy participants barely make compensatory saccades, as their VOR corrects for the head movement to maintain visual fixation on the earth-fixed target (Videos 2, 4).

Here we present a modified 'suppression' head impulse paradigm (SHIMP) resulting in a complementary saccadic pattern: Now the patient is instructed to follow a target from a head-mounted laser, which is moving with the head (Video 1). Patients with vestibular loss complete this task without corrective saccades, because their eyes move with the head (Videos 2, 3). Instead it is the healthy participants who make anti-compensatory saccades to regain the target after the head turn, because their healthy VOR drives their eyes off the head-fixed target (Video 2, 4).

Both paradigms provide two indicators of semicircular canal function: VOR gain and the presence of corrective saccades. While the VOR gain measures are predicted to be similar in both paradigms, the saccades are expected to be complementary: with HIMP, compensatory saccades indicate vestibular loss, whereas with SHIMP, anti-compensatory saccades indicate vestibular function. These predictions were tested in healthy participants and in patients with unilateral and bilateral vestibular loss.

MATERIALS AND METHODS

Standard Protocol Approvals and Patient Consents

Written informed consent was obtained from all participants and the protocol was approved by the Sydney South West Area Health Service Ethics Committee and the Cassino Ethics Committee in accordance with the Helsinki Declaration.

Participants

Participants were tested in Sydney, Australia and Cassino, Italy, between February and April 2011. Five patients (age range 37-73 years) with bilateral vestibular loss (BVL, two systemic gentamicin vestibulotoxicity, three idiopathic bilateral vestibular loss) fulfilled the inclusion criterion of a total caloric response of <30°/s (Table e-1).[5] Five patients with unilateral vestibular loss (UVL, operated unilateral vestibular Schwannoma with unilateral vestibular nerve transection, age range 40-70 years) were enrolled. Six participants (age range 28-68 years) without any history of vestibular disease served as healthy controls.

Study design

The case-control study was a prospective comparison of HIMP and SHIMP using vHIT to test horizontal semicircular canal function in healthy controls and patients with prior, independently identified vestibular deficits. In every case both testing paradigms were undertaken in the one testing session. The results of the study are reported in accordance with the STROBE statement.[6] The primary purpose of the study was to provide Class III evidence that the SHIMP accurately identifies patients with unilateral or bilateral vestibulopathies.

Experimental procedure.

1. HIMP. Participants were instructed to fixate an earth-fixed dot on a wall about 90cm away. Approximately 20 horizontal head impulses, with unpredictable timing and direction, were manually delivered by the experimenter to each side. Target peak head velocity of the impulses was about 150-250°/s. To preserve any corrective saccades, particular care was taken to minimize overshoot and return at the end of the head turn ("bounce").

2. SHIMP. Exactly the same procedure was used as for HIMP with the sole difference being that the participants were asked to fixate a target, which moved with the head. This target was a spot projected onto the wall in front of the participant by a miniature class 1 laser mounted onto the goggles.

Video-oculography. The methods for video head impulse recording have been described in detail previously.[2, 3, 7, 8] A high-speed, lightweight, digital video camera (Firefly MV, Point Grey Research Inc., Vancouver, BC) mounted on a glasses frame viewed the right eye via an infrared reflecting mirror and recorded eye position at a frame rate of 250Hz. The low weight of the system (~60g) minimized slippage of the glasses. Two infrared light emitting diodes (TSUS502, Vishay Intertechnology, Malvern, PA) run at 20mA illuminated the eye with infrared levels far below exposure risk levels.[9] Head velocity was measured by triaxial orthogonal gyroscopes (IDG-300, InvenSense, Santa Clara, CA) mounted on the glasses frame. The *in vivo* calibration of eye position required participants to fixate on projected targets from small lasers mounted on the glasses. A laptop running online programs in LabVIEW (National Instruments, Austin, TX) detected the pupil center by a center-of-gravity algorithm and a two point differentiator yielded eye velocity which was then low pass filtered (0-30Hz bandwidth) for further processing.[10]

Data analysis. Offline data analysis used customized LabVIEW software. Analysis bias was avoided by fully automated data analysis without manual interference. Each head impulse was detected and aligned at peak head acceleration.[4] If the eye velocity lay outside an envelope around the expected eye velocity response, it was classified as a blink or outlier and automatically excluded.[3] An eye acceleration algorithm was used to detect saccades, which were removed for VOR gain analysis.[2] The gain of the VOR for each impulse was calculated as the ratio of the area under the de-saccaded eye velocity to the area under the head velocity.[2] The points defining the boundaries of the head impulse were defined from the moment when head velocity exceeded 5% of peak head velocity to the moment when head velocity crossed zero again.[4] Cumulative HIMP and SHIMP saccade amplitude was calculated as the sum of the amplitudes of all saccades for each side divided by the number of trials. Weighted median HIMP and SHIMP saccade latency was calculated for each side as the median latency of all saccades weighted by their amplitudes.

Statistical analysis. Receiver operating characteristic (ROC) statistics were calculated with MedCalc software (Ostend, Belgium). To test whether VOR gains with standard HIMPs were significantly different from VOR gains with SHIMPs we used paired sample t-tests (significance level $p = 0.05$).[11] The goodness of fit of the linear correlation between VOR gains from HIMP and SHIMP was estimated by the coefficient of determination (R^2).

RESULTS

We measured horizontal vHIT in 6 healthy controls, 5 UVL and 5 BVL patients. We analyzed saccade patterns as well as VOR gains to compare SHIMP with a head-fixed target to conventional HIMP with an earth-fixed target (Table e-1).

Saccade analysis. For comparison of the saccadic pattern during SHIMP to conventional HIMP we juxtaposed examples of a healthy control (Figure 1), a BVL patient (Figure 2) and a UVL patient (Figure 3, see also videos 2-4). In all participants, SHIMP and HIMP resulted in a reversed saccadic pattern: During HIMP, healthy controls elicited only few positive catch-up saccades, while during SHIMP they elicited large negative saccades back to the head-fixed target after the end of the head impulse (Figure 1). BVL patients showed the opposite pattern with mostly overt saccades back to the stationary target during HIMP, but only few downward saccades during SHIMP (Figure 2). UVL patients often elicited covert saccades with impulses to the affected side during HIMP, but large downward saccades with impulses to the healthy side during SHIMP (Figure 3).

For summarizing the saccadic patterns in the different patient groups, histograms with cumulative saccade amplitude comprising all participants were calculated (Figure 4). For HIMP, positive saccades were cumulated as a function of latency after head impulse onset (upward histogram bars), while for SHIMP, negative saccades were cumulated (downward histogram bars).

Healthy controls elicited only few HIMP saccades, but a multitude of SHIMP saccades with a mean weighted median latency of 185ms ±20 SD, indicating normal vestibular function (Figure 4A). In contrast, BVL patients produced mainly HIMP saccades with a mean weighted median latency of 223ms ±35 SD (Figure 4C). But as bilateral vestibular loss was incomplete in some BVL patients, they also produced a few SHIMP saccades, indicating residual vestibular function. With 292ms ±69 SD the mean latency of these SHIMP saccades was significantly longer than the corresponding HIMP saccades in the same BVL patients ($p=0.0032$). Cumulative HIMP saccade amplitude with a >0.78°/trial cut-off discriminated BVL patients from healthy controls with 100% sensitivity (69-100 95% CI) and 100% specificity (74-100) and an area (AUC) under the Receiver Operating Characteristic (ROC) curve of 1.0 (0.85-1.0, $p<0.0001$, Table e-2). Cumulative SHIMP amplitude with a >-2.51°/trial cut-off discriminated BVL patients from healthy controls with 90% sensitivity (56-100) and 100% specificity (74-100) and AUC 0.99 (0.83-1.0, $p<0.0001$).

To their affected side, some UVL patients elicited covert HIMP saccades with weighted median latencies of 120-140ms, others only late overt saccades (mean weighted median latency 269ms ±128 SD) (Figure 4B). But UVL patients produced only overt SHIMP saccades with a mean weighted median latency of 238ms (±46 SD) to their affected side. To their healthy side, UVL patients produced almost no HIMP saccades and mostly overt SHIMP saccades with a mean weighted median latency of 202ms (±41 SD) (Figure 4D). Both cumulative HIMP saccade amplitude (>0.78°/trial) and SHIMP saccade amplitude (>-2.51°/trial) discriminated UVL patients on their affected side from healthy controls with 100% sensitivity (48-100) and 100% specificity (74-100) and AUC 1.0 (0.81-1.0, $p<0.0001$). While cumulative HIMP saccade amplitude could not discriminate between the healthy side of UVL and normals (AUC 0.51, $p=0.96$), cumulative SHIMP amplitude (>-5.18°/trial) distinguished the two with 80% sensitivity (28-100) and 83% specificity (52-98) and AUC 0.82 (0.56-0.96, $p=0.0049$).

VOR gain. Both HIMP gains (<0.76) and SHIMP gains (<0.66) discriminated BVL patients from normals with 100% sensitivity (69-100) and 100% specificity (74-100) and AUC 1.0 (0.85-1.0, p<0.0001, Table e-2). Similarly HIMP gains (<0.76) and SHIMP gains (<0.66) identified the affected side of UVL with 100% sensitivity (48-100) and 100% specificity (74-100) and AUC 1.0 (0.81-1.0, p<0.0001). For separating the healthy side of UVL from healthy controls both HIMP gains (<0.76) and SHIMP gains (<0.66) reached 60% sensitivity (15-95) but 100% specificity (74-100) with HIMP AUC 0.85 (0.60-0.97, p=0.0017) and SHIMP AUC 0.84 (0.59-0.97, p=0.0024).

The similarity of VOR gain measures for SHIMP and HIMP was compared across all patients and controls. SHIMP gains were slightly lower than HIMP gains (mean gain difference 0.06±0.05 SD, p<0.001). With the exception of the small gain values to the affected side in UVD patients, this difference was significant in all subgroups. The coefficient of determination confirmed close correlation (R^2=0.97) between the VOR gains of the two paradigms across all patients and controls (n= 16 participants × 2 sides).

vHIT model. Figure 5 illustrates the salience of saccades of different peak velocity with respect to their amplitude and VOR deficit. Ideally, HIMP elicits no saccades in healthy controls with unity gain (Figure 5A), while SHIMP elicits no saccades in patients with total BVL and zero gain (Figure 5J), as no corrective eye movements should be necessary under these conditions. Little residual VOR in SHIMP (Figure 5H), as well as small deficits in HIMP are sufficient to trigger saccades (Figure 5C). In the velocity domain, the size of these small saccades is overestimated by the naked eye, as the relationship between peak velocity and amplitude of saccades, often referred to as ‘main sequence’ [12], is nonlinear. The salience of these small saccades makes them a sensitive indicator of residual VOR function in SHIMP and subtle deficits in HIMP, respectively.

DISCUSSION

In this study we introduced a complementary head impulse paradigm (Video 1). While for traditional HIMP, participants were instructed to fixate an earth-fixed target, in SHIMP we asked them to follow a target that moved with the head. We have shown that the VOR gain measures for the two paradigms correlate well with slightly lower gain values for SHIMP compared to traditional HIMP. However, the observed saccadic patterns during the two paradigms were complementary: While the compensatory saccades opposite to the head movement in HIMP indicate vestibular loss, the appearance of anti-compensatory saccades with the head movement in SHIMP indicates vestibular function with high sensitivity and specificity (Videos 2-4).

Catch-up saccades during traditional HIMP directly reflect the clinical sign of canal paresis as observed by the physician at the bedside.[1] While overt saccades after the head movement are detectable by the naked eye, covert saccades during the head movement may be imperceptible to the clinical observer, as they cannot be distinguished from the residual VOR response.[4] Nevertheless, cumulative amplitude of overt saccades after the head movement has been shown to be a useful marker for vestibular loss complementary to the VOR gain.[13]

Contrary to HIMP, SHIMP saccades in the direction of head rotation indicate vestibular function rather than loss, as they have to correct for any VOR in order to bring the eyes back to the head-fixed target. Our study has shown that the appearance of anti-compensatory saccades in the direction of the head movement is a sensitive marker of residual vestibular function in SHIMP. Detecting residual vestibular function in patients with vestibular loss is of great clinical importance for vestibular rehabilitation, as it may help patients in compensating for their vestibular deficit by triggering early catch-up saccades.[14, 15]

Traditionally, the main measurement parameter for head impulse testing was VOR gain. VOR gain as the ratio between head and eye movement has usually been measured during the first 80-100ms before the appearance of the first catch-up saccades.[16] Unfortunately, this time window is most susceptible to video recording artifacts due to goggle slippage.[2, 17] Therefore, we recently proposed an improved algorithm, which calculates gain during the entire head impulse, but removes any catch-up saccades that can interfere with accurate VOR measures, prior to analysis.[2] As SHIMP saccades usually appear after the end of the head impulse, SHIMP eliminates most catch-up saccades in the sensitive time period for VOR gain calculation during the head impulse in patients with unilateral vestibular loss (Figure 3, affected side), thus facilitating more accurate gain measurements under these conditions. This may be of particular advantage in patients with acute vestibular neuritis, as SHIMP clears the head impulses to the affected side from contamination with spontaneous nystagmus.

Previous evidence has shown that healthy controls can, after a delay, suppress their slow phase eye velocity response elicited by semicircular canal stimulation. Crane and Demer found that the latency of VOR suppression with a visual target during high acceleration whole-body rotations was about 80-90 ms.[18] Therefore it may be expected that participants would be able to suppress their VOR to some extent during the head turn in SHIMP. Indeed, we found slightly, but significantly lower VOR gains during SHIMP compared to HIMP. Correspondingly, the only subgroup, which did not show such a difference, was the one with the UVD patients to the affected side, where VOR gains were low *a priori*. Alternatively, the de-saccading algorithm,[2] which is used to remove the catch-up saccades during the time window for VOR gain measurements may be responsible for this systematic difference. This, in turn, would be an additional argument in favor of SHIMP, as it usually delays any saccades until after the end of the head impulse.

Proper vHIT examination technique is crucial to avoid measurement artifacts.[17] For accurate VOR gain measurements, ballistic head impulses of sufficient speed (ideally ~200°/s) are important, while tight goggle fit must be ensured to avoid slippage. For the subsequent saccade pattern, the ending of the impulse is of paramount importance. Overshoot (‘bounce’) of the head at the end of the impulse is destructive, as it diminishes the amplitude of both SHIMP saccades and HIMP saccades. The ideal head impulse is therefore a position step (‘turn and stop’) rather than a bounce. Hence, a skilled operator and sufficient practice are necessary to ensure good examination quality.

We have found that SHIMP is equally simple to explain to patients as conventional HIMP, and patients reported that the task is easy to perform, comparing it to watching the ball during a tennis match. It is an easy intuitive task and the “game-like” test situation provides accurate, objective, measures of vestibular function and saccadic compensation. The head-fixed target can be a cyclist’s headlamp or a laser pointer on a bite bar, projecting a spot on the wall. SHIMP saccades can even be observed at the bedside: The clinician, standing to one side, can see SHIMP saccades easily since they are usually very large and later than HIMP saccades. In contrast to HIMP saccades, which are a sensitive indicator of vestibular loss, SHIMP saccades are a clinical sign of vestibular function. Therefore, the two complementary paradigms have their diagnostic strengths at opposite ends of the vestibular disease spectrum. Routine application will be necessary to acquire more experience about the clinical utility of

SHIMP at the bedside and further studies will be needed to determine its diagnostic accuracy in vHIT measurements.

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LEGENDS

Figure 1: Video head-impulse test of a healthy control with SHIMP (bottom) compared to conventional HIMP (top).

During SHIMP (bottom) the participant's task is to fixate a target, which is moving with the head, whereas in conventional HIMP (top) the target remains stationary. The figure illustrates the typical HIMP and SHIMP saccade pattern in a healthy control. (Top) During conventional HIMP a healthy control elicits only few mostly positive catch-up saccades (red) after the end of the head impulse. (Bottom) During SHIMP the same healthy control shows large negative saccades after the end of the head impulse reflecting anti-compensatory eye movements back to the head-fixed target. Both paradigms give similar, but slightly lower VOR gain values during SHIMP compared to HIMP, but a complementary saccade pattern. Head velocity: green traces. Inverted slow phase eye velocity: blue traces. Saccades: red traces.

Figure 2: Video head-impulse test of a BVL patient with SHIMP (bottom) compared to conventional HIMP (top).

Typical patient with complete BVL showing a reversed saccadic pattern during HIMP and SHIMP compared to a healthy control (Figure 1). (Top) During standard HIMP the BVL patient elicits mostly overt positive catch-up saccades after the head impulse. (Bottom) During SHIMP the same BVL patient shows only very few downward saccades reflecting anti-compensatory saccades after the end of the head impulse back to the head-fixed target. Both paradigms give similar, but slightly lower VOR gain values during SHIMP compared to HIMP, but a complementary saccade pattern, which is reversed compared to healthy controls. Head velocity: green traces. Inverted slow phase eye velocity: blue traces. Saccades: red traces.

Figure 3: Video head-impulse test of a UVL patient with SHIMP (bottom) compared to conventional HIMP (top).

Typical UVL patient showing reversed saccadic patterns during HIMP compared to SHIMP to the healthy and affected side. (Top right) With standard HIMP, the patient elicits stereotyped covert saccades during head impulses to the affected side. (Bottom right) With SHIMP, the patient elicits only small negative saccades after impulses to the affected side. Note that compared to HIMP (top right), SHIMP (bottom right) clears the eye velocity traces from covert saccades during head impulses to the affected side, thus facilitating gain calculation. Head impulses to the healthy side produce only small negative saccades during HIMP (top left), but large negative saccades during SHIMP (bottom left). VOR gain values to the healthy side are slightly lower during SHIMP compared to HIMP, but very similar to the affected right side. Head velocity: green traces. Inverted slow phase eye velocity: blue traces. Saccades: red traces.

Figure 4: Cumulative saccade amplitude as a function of latency after head impulse onset.

(A) In healthy controls, HIMP elicits only few saccades (upward histogram bars), while SHIMP elicits a multitude of saccades (downward histogram bars) with a peak latency of about 176ms. (C) BVL patients show a reversed saccadic pattern with large saccades in HIMP, but only few saccades in SHIMP. UVL patients often produce covert HIMP saccades with head impulses to the affected side (B) and overt SHIMP saccades to the healthy side (D). Note that in the same UVL patients overt SHIMP saccades to the healthy side (D) have a longer peak latency (176ms) compared to the covert HIMP saccades to the affected side (104ms, B). Histogram bars represent summated amplitudes of HIMP saccades (positive) and SHIMP saccades (negative) in 8-msec bins after head impulse onset. Saccade amplitude was normalized relative to the number of head impulses and participants and kept in proportion between participant groups (A, n = 6 controls × 2 sides), UVL patients (B: affected side, D: healthy side, n = 5) and BVL patients (C, n = 5 × 2).

Figure 5: vHIT model for illustration of saccade size in relation to VOR gain deficit. (A) In a healthy control, a head impulse with an earth-fixed target (HIMP) elicits no saccade. (B) In the same healthy control with a VOR gain of one, a head impulse with a head-fixed target (SHIMP) elicits an anti-compensatory saccade of the size of the head rotation (16.5°). (J) Conversely, in a total BVL patient with a VOR gain of zero, SHIMP elicits no saccade, (I) while HIMP elicits a saccade of the size of the head rotation. (C) Little VOR loss (gain 0.9) is sufficient to elicit a small compensatory saccade with HIMP. (H) In a patient with incomplete vestibular loss, little residual function (gain 0.1) is sufficient to elicit a small anti-compensatory saccade with SHIMP. Note that upon visual inspection in the velocity domain, the amplitude of smaller saccades (C: 1.5° amplitude) is over-estimated compared to the amplitude of larger saccades (I: 15.8° amplitude).

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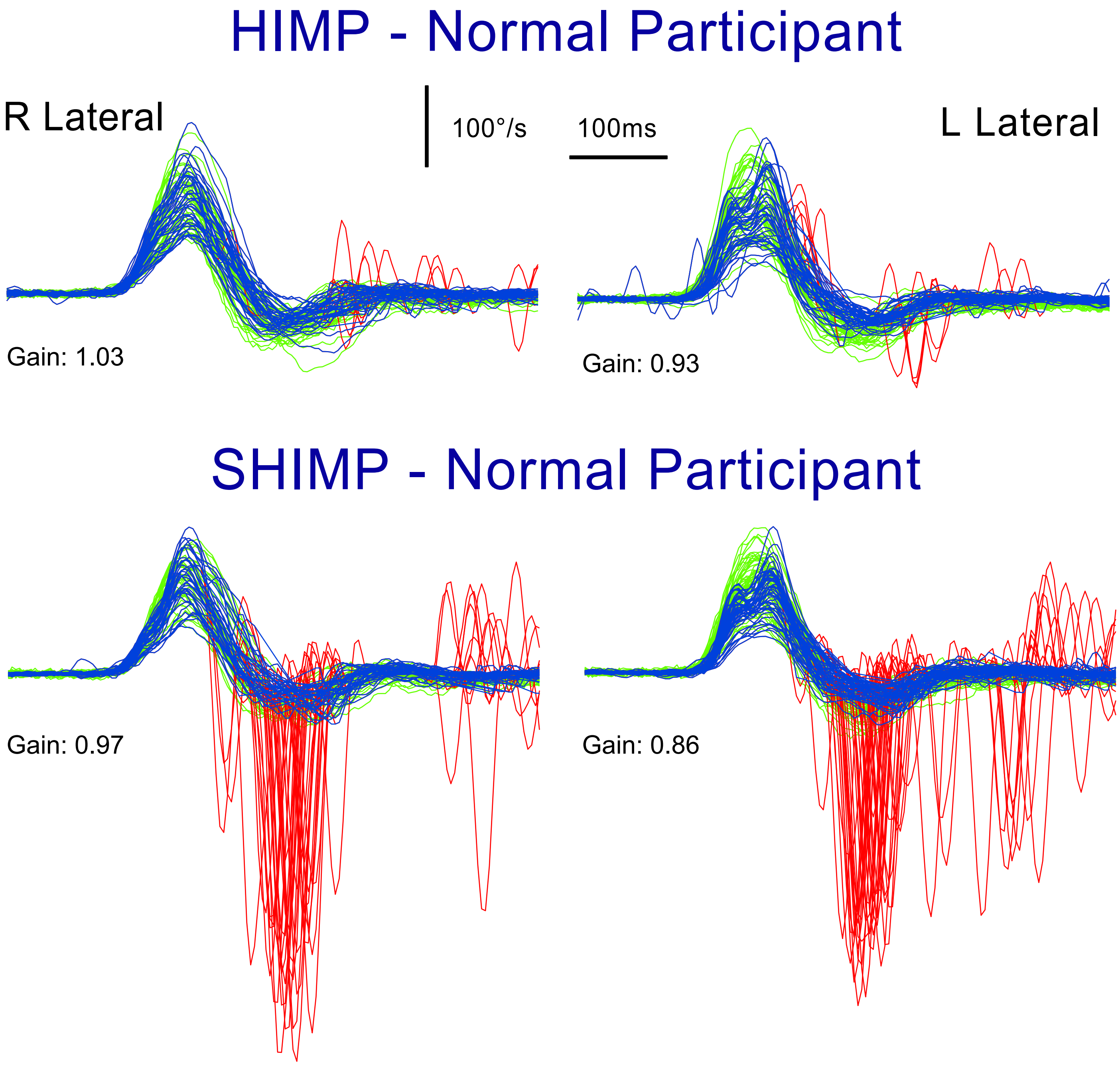
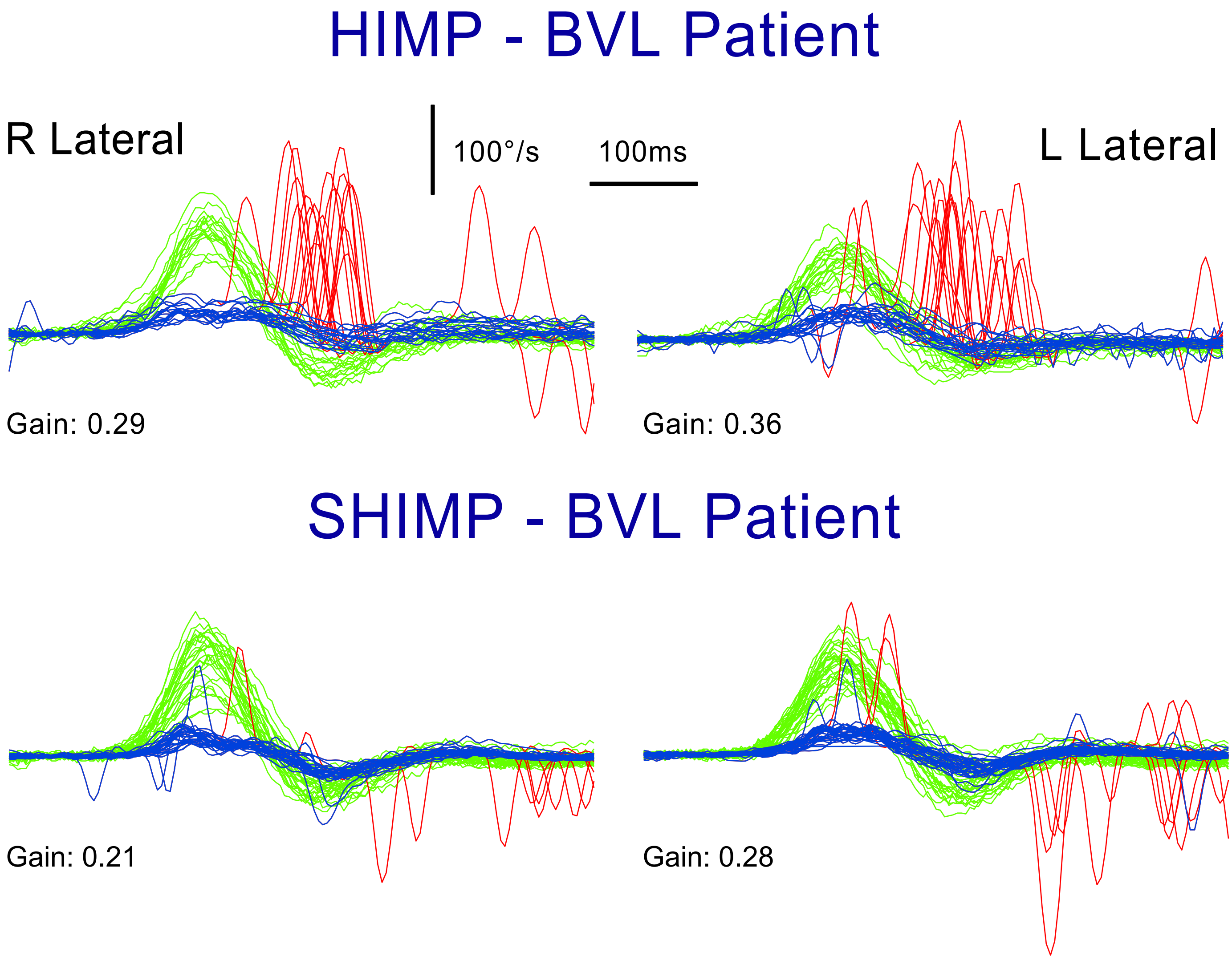
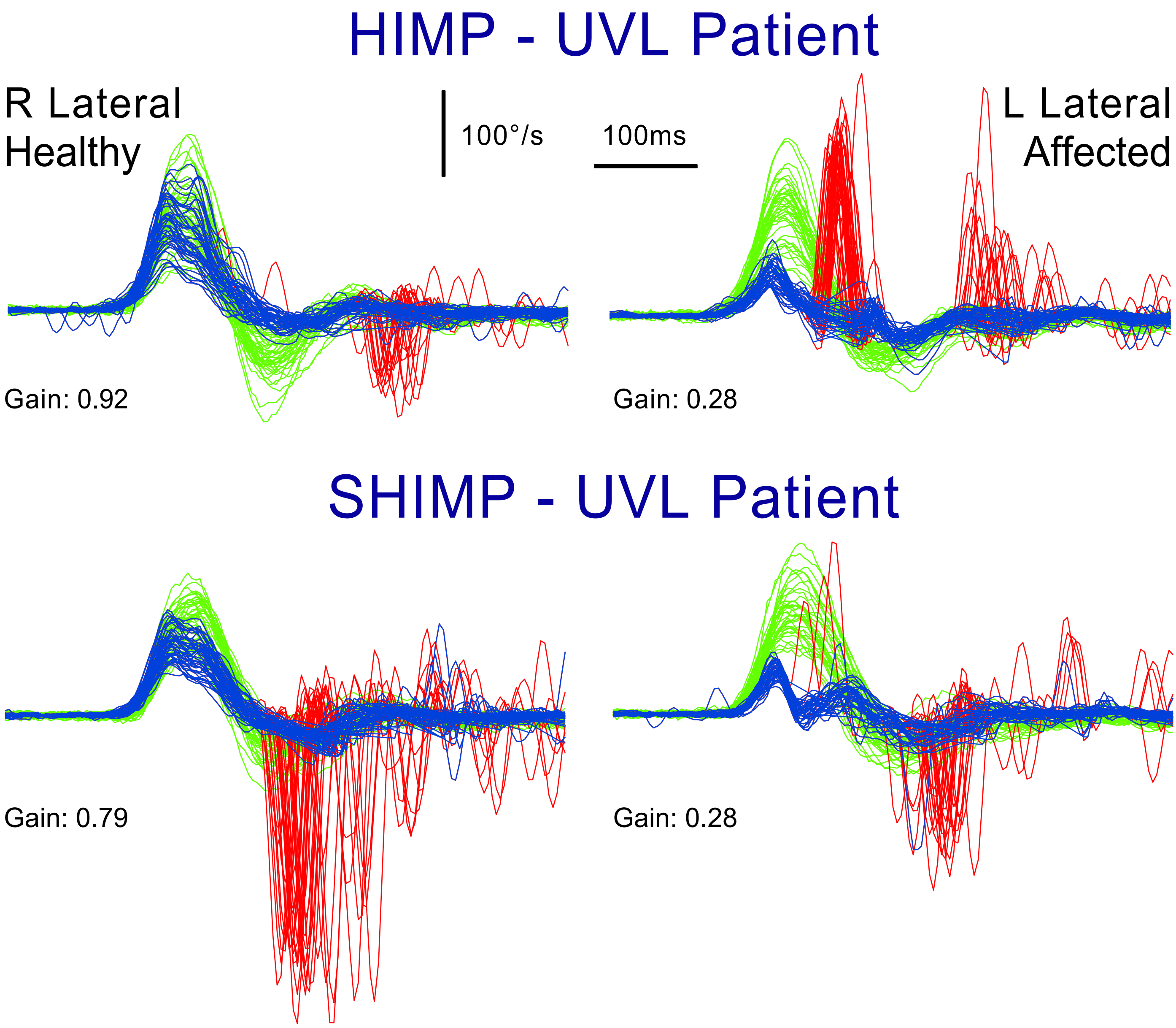
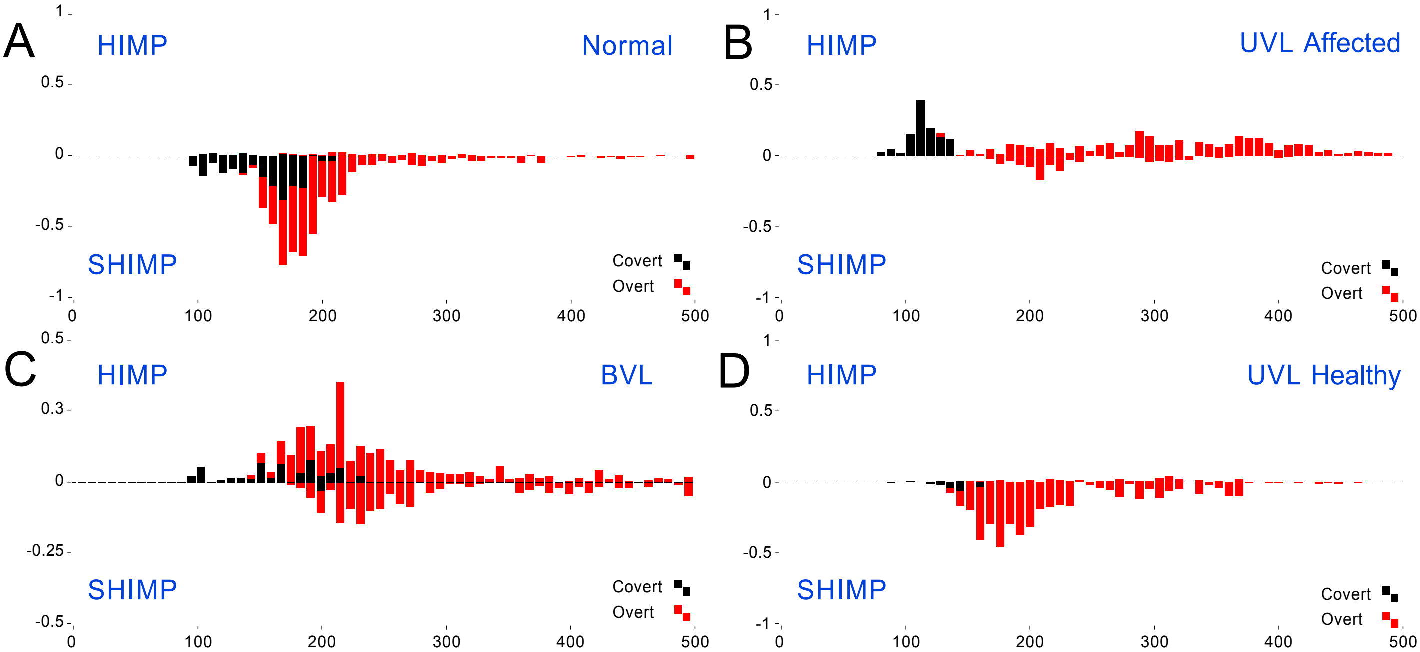
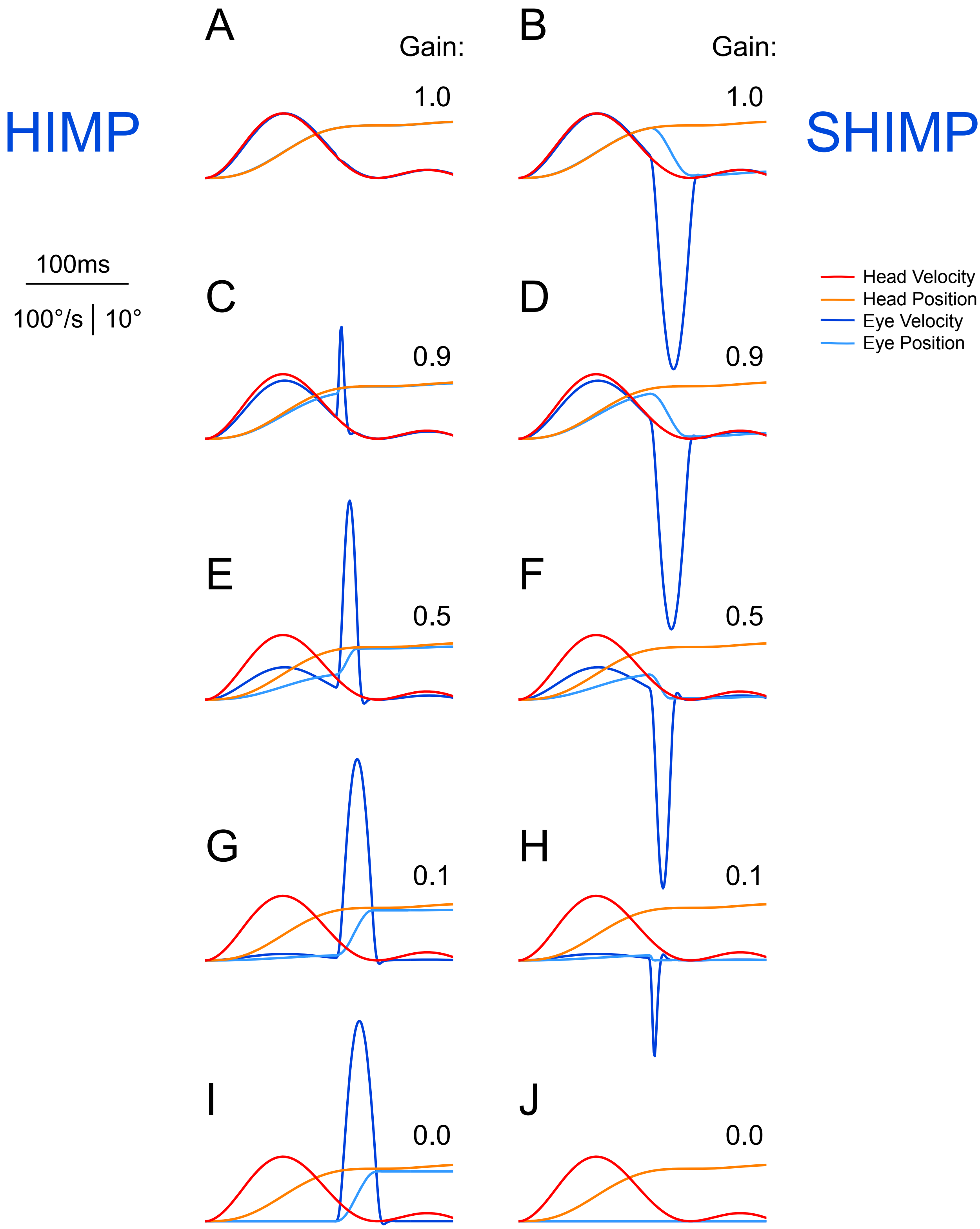

HIMP - Normal Participant
R Lateral
100°/s
100ms
L Lateral
Gain: 1.03
Gain: 0.93
SHIMP - Normal Participant
Gain: 0.97
Gain: 0.86


HIMP - BVL Patient
R Lateral
100°/s
100ms
L Lateral
Gain: 0.29
Gain: 0.36
SHIMP - BVL Patient
Gain: 0.21
Gain: 0.28


HIMP - UVL Patient
R Lateral
Healthy
100°/s
100ms
L Lateral
Affected
Gain: 0.92
Gain: 0.28
SHIMP - UVL Patient
Gain: 0.79
Gain: 0.28



A
HIMP
Normal
SHIMP
Covert
Overt
B
HIMP
UVL Affected
SHIMP
Covert
Overt
C
HIMP
BVL
SHIMP
Covert
Overt
D
HIMP
UVL Healthy
SHIMP
Covert
Overt



HIMP
SHIMP
A
B
Gain:
Gain:
1.0
1.0
100ms
100°/s | 10°
C
D
0.9
0.9
E
F
0.5
0.5
G
H
0.1
0.1
I
J
0.0
0.0
Head Velocity
Head Position
Eye Velocity
Eye Position

Table e-1: Clinical and demographical characteristics and video head impulse measures of normal participants and patients with unilateral and bilateral vestibular loss.

Diagnosis	Age Gender	Total caloric response (°/s)	HIMP R gain	HIMP L gain	SHIMP R gain	SHIMP L gain	Cumulative HIMP saccade amplitude R (°/trial)	Cumulative HIMP saccade amplitude L (°/trial)	Cumulative SHIMP saccade amplitude R (°/trial)	Cumulative SHIMP saccade amplitude L (°/trial)	HIMP Weighted median saccade latency R (ms)	HIMP Weighted median saccade latency L (ms)	SHIMP Weighted median saccade latency R (ms)	SHIMP Weighted median saccade latency L (ms)
Normal	39 m	-	0.88	0.90	0.76	0.77	0.78	0.55	-5.94	-6.57	176	140	156	188
Normal	42 m	-	1.01	0.94	0.96	0.88	0	0	-5.18	-5.79	-	-	168	160
Normal	50 m	-	1.03	0.88	0.96	0.78	0.06	0	-8.16	-8.22	-	-	172	192
Normal	68 m	-	0.86	0.76	0.72	0.66	0.22	0.34	-2.51	-3.1	208	220	220	220
Normal	34 m	-	0.96	0.85	0.92	0.83	0.69	0.16	-5.96	-6.39	248	248	184	196
Normal	28 m	-	1.03	0.93	0.97	0.86	0.16	0.23	-6.82	-5.36	228	496	180	184
Idiopathic BVL	60 m	<10	0.60	0.73	0.52	0.63	3.05	1.39	-1.46	-0.53	248	256	264	364
Gentamicin BVL	46 m	<10	0.29	0.36	0.21	0.28	3.71	3.69	-0.56	-0.75	212	220	388	324
Idiopathic BVL	37 f	13	0.48	0.59	0.45	0.48	2.37	2.85	-2.25	-0.75	264	272	272	388
Idiopathic BVL	64 m	15	0.44	0.52	0.42	0.48	3.60	2.88	-2.42	-1.29	192	200	232	244
Gentamicin BVL	73 m	28	0.47	0.38	0.46	0.37	0.83	2.08	-2.59	-1.49	188	176	208	232
			affected	**healthy**	**affected**	**healthy**	**affected**	**healthy**	**affected**	**healthy**	**affected**	**healthy**	**affected**	**healthy**
L operated Schwannoma	40 f	-	0.28	0.92	0.28	0.79	4.79	0.05	-1.61	-4.49	120	-	208	168
R operated Schwannoma	70 m	-	0.34	0.62	0.26	0.59	3.70	0	-0.16	-5.23	336	-	240	200
R operated Schwannoma	70 m	-	0.27	0.66	0.31	0.56	4.29	0.33	-0.69	-3.42	376	316	200	192
L operated Schwannoma	48 m	-	0.35	0.67	0.34	0.63	3.54	0.48	-1.45	-3.19	140	240	228	180
R operated Schwannoma	63 f	-	0.39	0.87	0.44	0.78	4.70	0.26	-0.72	-5.14	372	352	316	272

Total caloric response = sum of peak slow phase eye velocities (°/s) from all four caloric irrigations (cold right + cold left + warm right + warm left). HIMP = conventional head impulse paradigm with earth-fixed target. SHIMP = suppression head impulse paradigm with head-fixed target. Compensatory HIMP saccades with positive signs, anti-compensatory SHIMP saccades with negative signs. BVL = bilateral vestibular loss. Results from patients with left unilateral vestibular loss (operated Schwannoma) are mirrored to the right to improve the readability of the table. Weighted median saccade latency was not calculated in participants with cumulative saccade amplitude < 0.1°/trial.

Table e-2: Receiver operating characteristic (ROC) analysis.

Classifiers	Parameter	Paradigm	Optimal cut-off	Sensitivity	Specificity	Area under the ROC curve	Significance level (area = 0.5)
Normal (2 × 6 ears) vs. BVL (2 × 5 ears)	Gain	HIMP	<0.76	100% (69-100)	100% (74-100)	1.0 (0.85-1.0)	p<0.0001
		SHIMP	<0.66	100% (69-100)	100% (74-100)	1.0 (0.85-1.0)	p<0.0001
	Cumulative saccade amplitude	HIMP	>0.78°/trial	100% (69-100)	100% (74-100)	1.0 (0.85-1.0)	p<0.0001
		SHIMP	>-2.51°/trial	90% (56-100)	100% (74-100)	0.99 (0.83-1.0)	p<0.0001
Normal (2 × 6 ears) vs. UVL affected (5 ears)	Gain	HIMP	<0.76	100% (48-100)	100% (74-100)	1.0 (0.81-1.0)	p<0.0001
		SHIMP	<0.66	100% (48-100)	100% (74-100)	1.0 (0.81-1.0)	p<0.0001
	Cumulative saccade amplitude	HIMP	>0.78°/trial	100% (48-100)	100% (74-100)	1.0 (0.81-1.0)	p<0.0001
		SHIMP	>-2.51°/trial	100% (48-100)	100% (74-100)	1.0 (0.81-1.0)	p<0.0001
Normal (2 × 6 ears) vs. UVL healthy (5 ears)	Gain	HIMP	<0.76	60% (15-95)	100% (74-100)	0.85 (0.60-0.97)	p=0.0017
		SHIMP	<0.66	60% (15-95)	100% (74-100)	0.84 (0.59-0.97)	p=0.0024
	Cumulative saccade amplitude	HIMP	-	-	-	0.51 (0.26-0.75)	p=0.96
		SHIMP	>-5.18°/trial	80% (28-100)	83% (52-98)	0.82 (0.56-0.96)	p=0.0049

BVL = bilateral vestibular loss. UVL = unilateral vestibular loss. HIMP = conventional head impulse paradigm with earth-fixed target. SHIMP = suppression head impulse paradigm with head-fixed target. Compensatory HIMP saccades with positive signs, anti-compensatory SHIMP saccades with negative signs. Sensitivity, specificity and area under the ROC curve with 95% confidence intervals in brackets. Sensitivity, specificity and cut-off were not calculated where the ROC curve was not significant.